

KREEP, KREEP derivatives and the Lunar D Enrichment

K.L. Robinson (1), G.J. Taylor (1), E. Hellebrand (2), and K. Nagashima (1)

(1) Hawaii Inst. of Geophysics and Planetology (2) Geology and Geophysics, University of Hawaii at Manoa, 1680 E. West Rd., Honolulu, HI 96822 USA. krobinson@higp.hawaii.edu

Abstract

Here we present δD and H_2O content measurements for residual glass in KREEP basalt, which build on our measurements of lunar apatites found in the evolved, KREEP-derivative felsites and quartz monzodiorites. The extremely low water content of the KREEP basalt and the evolved rocks suggests that their respective source regions were dry compared to that of the mare basalts.

Introduction

The source of water for the terrestrial planets has important implications for accretion processes and dynamical conditions in the early inner solar system. A powerful tool for determining water sources is the D/H ratio because different solar system water reservoirs have unique D/H ratios. Water has now been detected in lunar pyroclastic glasses [1], apatites [2], melt inclusions [3], and residual glass (this work). The source of this interior lunar water is not known, but may be elucidated through study of the D/H ratio of water in lunar apatite [4-6].

Yellow glass has been reported in KREEP basalt clasts in impact breccia 15358,6 [7]. This glass is significant because it is the quenched remnants of the last 15-20% of the bulk KREEP basalt melt. The presence of water in this remaining glass could allow us to make a rough estimate about the water content of the initial KREEP basalt magma, as well as estimated water abundances for KREEP-derived rocks.

Apatite $[Ca_5(PO_4)_3(F,Cl,OH)]$ incorporates water as OH into its crystal structure, and resists isotopic exchange with H and O in Earth's atmosphere [4]. The H_2O abundance of apatite in various lunar rocks ranges widely. Apatites in mare basalts seem to have the highest H_2O content (0.7wt% in Northwest Africa 2977, [2]), while apatites in the more evolved, KREEP-related rocks have very little H_2O (<0.03wt% [2,4,5]).

KREEP and Evolved Lunar Volcanism

The felsites and the quartz monzodiorites are fractional crystallization products of KREEP basalts (rich in **K**, Rare Earth Elements, and **P**) [8]. The felsites are evolved intrusive Si-rich rocks displaying graphic intergrowths of quartz and K-feldspar, sometimes occurring in samples with a coexisting ferrobasalt [8]. The quartz monzodiorites (QMDs) are similarly evolved rocks, but with a cumulate texture.

The intrusive nature of felsites and the QMDs suggests that they may have been able to escape degassing of any water that was present in their respective source magmas. Up to 1% water is soluble in basalt and rhyolite melts at modest pressures on the Moon (~1kbar or 2km depth; calculated with [10]). This makes the evolved rocks ideal for preserving H_2O of their parent magmas and interior source region(s).

Elkins-Tanton and Grove [9] observed that this lack of water in apatite in the KREEP-related rocks is unexpected. Water acts like an incompatible element at low abundances, which means it will become enriched in a crystallizing melt. Thus, KREEP or KREEP-rich magmas should be enriched in water when apatite crystallizes. However, measurements for evolved rocks [2,4,5] indicate that they contained very little water, which implies that their source regions also contained very little water [9].

Methods and Results

Residual glass in KREEP basalt clasts in 15358, 6 was measured for D,H, and ^{30}Si on the UH ims 1280 ion microprobe using a 4.0nA Cs+ primary beam in March 2012. H_2O content of the glass was estimated using a H_2O (wt%) vs. $H/^{30}Si$ calibration curve using 2 terrestrial glass standards. The March 2012 detection limit was 10ppm, with δD and H_2O content uncertainties of ~80‰ and 11ppm.

Apatites in felsites 14321,1047 and 77538,16, and QMDs 14161, 7069 and -,7373 were analysed in situ for D, H and ^{18}O on the same instrument using a 2.0nA Cs⁺ primary beam in two sets of measurements in May and Nov. 2011. H₂O content of apatite samples was estimated from a H₂O (wt.%) vs. $^{1\text{H}}/\text{H}^{18}$ calibration curve determined using 3 terrestrial apatite standards after [4,5]. The detection limit was ~100-110 ppm, with δD and H₂O content uncertainties of 60-74 %o and 30%.

Residual glass in KREEP basalt 15358,6 had 58-95ppm H₂O and δD ~610- 830‰. Apatite in felsite 14321,1047 and two apatites in 14161,7373 had H₂O content below our detection limits. One apatite in QMD 14161,7069 and one in -,7373 had H₂O content at our detection limits. Apatite in 77538,16 contained ~180ppm H₂O, with δD of ~300-400‰ [5].

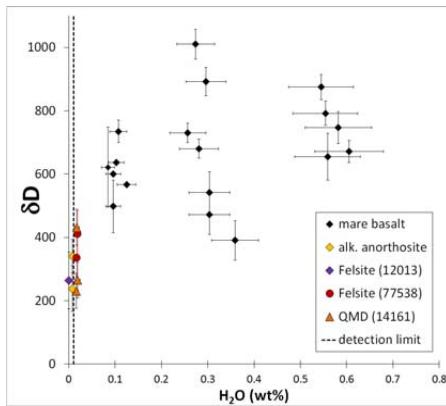


Fig. 1. δD vs. H₂O plot of lunar apatites by rock type. The evolved, KREEP-related rocks cluster at very low H₂O abundance and lower δD . Data from [4] plotted as diamonds. Dashed line shows Nov. detection limit of 110ppm.

Discussion

We found very little water in the apatites and KREEP basaltic glass. This supports the hypothesis that that the KREEP component and the lunar magma ocean had low initial water content, as argued by [9], and the idea that the mare basalt source regions were distinctly richer in H₂O, perhaps due to incorporation from external sources [4,9,11]. The δD of hydrogen in all samples is elevated, with which supports the findings in [4] that the Moon is elevated in D compared to Earth. However, the δD in the felsites and the QMDs appears to be lower than the erupted

mare basalts and KREEP basalts, perhaps reflecting less loss from these intrusive rocks.

The origin of the Moon's water and apparent D enrichment are still unclear. Calculation of simple Rayleigh fractionation during water loss from the protolunar disk [12] shows that D enrichment occurs if hydrogen occurs primarily as H or D, likely under the reducing conditions, and that initial OH in the orbiting magma is continuously converted to H (Fig. 2). It is plausible that lunar water is dominated by water added after lunar formation. If so, the data suggest that the added materials had high δD .

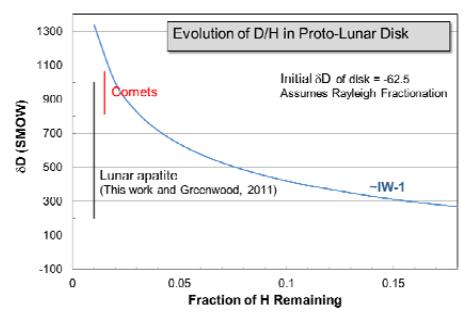


Fig. 2 D/H in the proto-lunar disk. Data from [4,5] and this work.

References

- [1] Saal A.E. et al. (2008) *Nature* 454:192-195.
- [2] McCubbin F.M. et al. (2010) *PNAS* 27:11223-11228.
- [3] Hauri E.H. et al. (2011) *Science* 333:213-215.
- [4] Greenwood J.P. et al. (2011) *Nat. Geosci.* 4:79-82.
- [5] Robinson K.L. et al. (2012) Ab# 1727, 43rd LPSC
- [6] Barnes J.J. et al. (2012) Ab#1797, 43rd LPSC
- [7] Taylor G.J. et al. (2012) *MAPS* 47:861-879
- [8] Robinson K.L., Taylor G.J. (2011) Ab#1257, 42nd LPSC
- [9] Elkins-Tanton L.T, Grove T.L. (2011) *EPSL* doi:10.1016/j.espl.2011.04.027
- [10] Newman S., Lowenstern J.B. (2002) *Comp. Geosci.* 28:597-604.
- [11] Bottke W.F. et al. (2010) *Science* 330:1527-30.
- [12] Desch, S. J. and Taylor, G. J. (2012) Volatile depletion from the protolunar disk. This conference.